TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Surface waviness and rib stitching have been investigated as part of a series of tests to determine the effects on wing drag of common surface irregularities. The tests were made in the N.A.C.A. 8-foot high-speed wind tunnel at Reynolds Numbers up to 17,000,000.

The results of the tests showed that the waviness common to airplane wings will cause no serious increase in drag unless the waviness exists on the forward part of the wing, where it may cause premature transition or premature compressibility effects. Waves 3 inches wide and 0.048 inch high, for example, increased the drag 1 percent when they covered the rear 67 percent of both surfaces and 10 percent when they covered the rear 92 percent. A single wave 3 inches wide and only 0.020 inch high at the 10.5-percent-chord point on the upper surface caused transition to occur on the wave and increased the drag 6 percent.

Rib stitching increased the drag 7 percent when the rib spacing was 6 inches; the drag increment was proportional to the number of ribs for wider rib spacings. About one-third of the increase was due to premature transition at the forward ends of the stitching.

INTRODUCTION

The N.A.C.A. has recently conducted tests to determine the effects on wing drag of surface irregularities common to present-day airplanes. Results showing the effects of various sizes and arrangements of protruding and countersunk rivet heads, of spot welds, of several types of lapped sheet-metal joints, of imperfections in butted joints, of surface roughness, and of manufacturing irregularities have been published in reference 1. The present note gives results showing the effect on wing drag of surface waviness such as occurs on sheet-metal and plywood-covered wings and of rib stitching such as occurs on fabric-covered wings. The tests were made in the N.A.C.A. 8-foot high-speed wind tunnel at Reynolds Numbers up to 17,000,000.

APPARATUS

The N.A.C.A. 8-foot high-speed wind tunnel, in which the tests were conducted, has a closed circular test section. Sphere tests have shown virtually the same critical Reynolds Number as in free air (reference 2).

An N.A.C.A. 23012 airfoil of 5-foot chord was used for the tests. The surface of the airfoil was aerodynamically smooth; that is, further polishing would not reduce the drag.

The airfoil was mounted horizontally across the center of the test section as shown in figure 1. The tunnel-wall interference was reduced by enclosing the ends of the airfoil in shields that did not touch the airfoil or its supports but were supported independently of the balance. The span of each shield was 10 inches and the active span of the airfoil between the shields was 6 feet. The airfoil extended 1 inch into each shield and the gap between the airfoil and the shields was 1/8 inch.

The two-dimensional waves (fig. 2) were approximately sinusoidal in cross section and had straight-line elements parallel to the span. The higher waves were constructed by cementing to the airfoil linoleum strips of the required cross section, filling the cracks between the strips with wax, sandpapering the whole with No. 400 sandpaper, and polishing. Waves less than 0.048 inch high were built up on the airfoil with several layers of successively narrower strips of paper. The steps at the edges of the strips were filled and the whole was faired over with lacquer-base glazing putty to give the desired sinusoidal cross-sectional profile and a smooth surface. The three-dimensional waves were circular in plan form and were similarly constructed with disks of paper (fig. 3).

Rib stitching was simulated as indicated in figures 1 and 4. Reinforcing tape was first doped to the airfoil, short transverse pieces of rib cord were placed on the tape, and pinked tape was then doped over both. The surface of the tape was lightly sandpapered after doping and the airfoil surface between the tapes was smooth.

METHOD

The drag was determined from force measurements at lift coefficients of approximately 0, 0.15, and 0.30 over speed ranges from 80 to 430, 80 to 370, and 80 to 270 miles per hour, respectively. The drag of the smooth true airfoil was frequently checked during the tests.

For the circular waves and the thinner two-dimensional waves, the movement of the transition point caused by the waves was determined by surface tubes. Some of the tubes are shown in figure 3.

The method used for determining the dynamic pressure, the air speed, and the Reynolds Number is described in reference 1.

PRECISION

Owing to constriction effects (explained more fully in reference 1), the drag increments herein presented may be high by as much as 6 percent of the increments at speeds up to 270 miles per hour and by as much as 9 percent at higher speeds. The drag increments being small relative to the smooth-wing drag, these systematic errors are unimportant.

The slight scatter of the experimental points and the agreement between the separate determinations of the smooth-wing drag indicate that the maximum random error due to balance friction, to fluctuation of the air flow, and to variation of the condition of the airfoil surface was about 1.4 percent of the smooth-wing drag at speeds between 100 and 400 miles per hour and at lift coefficients of 0 and 0.15. At speeds below 100 and above 400 miles per hour and at all speeds at a lift coefficient of 0.30, the maximum random error was less than 3 percent.

METHOD OF PRESENTATION

All results are presented as increases in drag coefficient over that for the smooth airfoil at the same speed and angle of attack. Because the results are presented as increments of drag coefficient, no corrections for tunnel-wall effects are required except for those due to constriction effects, which have been discussed under Precision.

The basic plots (figs. 5, 6, 7, and 10) of this paper show the variation of the drag increments with Reynolds Number. The test speeds corresponding to Reynolds Numbers of 10,300,000 and 17,600,000 were 0.3 and 0.6 the speed of sound, respectively.

SURFACE WAVINESS

The increases in drag coefficient caused by the two-dimensional waves are shown in figure 5 for waves covering both surfaces from the 8-percent-chord point to the trailing edge and, in figure 6, for waves covering both surfaces from the 33-percent-chord point to the trailing edge. Figure 7 shows the drag due to single waves of the same type with the center of the waves 10.5 percent of the chord from the leading edge.

The increase of the drag increments at Reynolds Numbers above 14,000,000, corresponding to a Mach number (the ratio of the air speed to the speed of sound in the air) of 0.42 and to a speed of 320 miles per hour under standard sea-level conditions, was probably due to compressibility effects rather than to scale effect. As was stated in reference 1, this result emphasizes that, for high-speed airplanes, it is important not only to choose suitable wing sections but also to construct the wings to conform accurately to the chosen sections.

Figure 8 shows that, within the range of the tests, the magnitude of the drag increment is chiefly dependent on the ratio of wave height to wave pitch. For geometrically similar waves (those having equal ratios of height to pitch), however, the smaller waves cause slightly larger increases in drag, as would be expected because the smaller waves produce larger absolute pressure gradients.

The dashed line near the bottom of figure 8 shows the computed increment of skin-friction drag resulting from the increased surface area and the increased velocity caused by the waves on the rear 67 percent of the airfoil. The fact that this increment is only about one-sixth as large as the measured drag increase indicates that most of the drag caused by the waves was form drag rather than skin-friction drag.

The flattest waves for which the drag was measured, 7.5 inches wide by 0.120 inch high (fig. 2) and 3 inches wide by 0.048 inch high, were relatively higher than the ones that usually occur on wings made according to present standards of workmanship. Even so, when these waves covered the rear 67 percent of both surfaces of the airfoil, they increased the drag only about 1 percent for most of the test range. When these same waves covered the rear 92 percent of both surfaces of the airfoil, they increased the drag 6 and 10 percent for the 7.5-inch and the 3-inch waves, respectively.

Figure 9 shows in detail that waves, as well as other surface irregularities, cause disproportionately large increases in drag when they occur forward of the smooth-wing transition point (on the upper surface at the 21-percent-chord position for the conditions of this figure). Comparison of figures 6 and 7 also illustrates this fact; for example, at a lift coefficient of 0.15 and a Reynolds Number of 10,300,000, a single 3- by 0.048-inch wave centered 10.5 percent of the chord from the leading edge on the upper surface increased the drag six times as much as waves of the same size covering the entire rear two-thirds of both surfaces of the airfoil. The drag increment caused by the single waves was about equal to the increment that would be expected from a shift of the transition point forward to the center of the wave. (See fig. 16 of reference 1.) The conclusion follows that, forward of the smooth-wing transition point, the wing should be free from waviness but that waviness of ordinary proportions may be tolerated back of the transition point.

Waves of relatively small height having been found to cause serious increases in drag only when they induce premature transition, tests were made to ascertain the smallest wave that would cause premature occurrence of transition. The results showed that waves 3 inches wide on the upper surface of the airfoil 10.5 percent of the chord from the leading edge caused transition to occur on the waves unless they were less than 0.020 inch high. A single wave only 0.020 inch high and 3 inches wide would therefore increase the drag about 6 percent at a lift coefficient of 0.15 and a Reynolds Number of 10,300,000.

Calculations based on the method suggested in reference 3 indicate that a wave 0.016 inch high and 3 inches wide will produce a pressure gradient just large enough to cause laminar separation, and therefore transition, to occur on the wave. The pressure gradient over such a wave is so large relative to the gradient over the normal airfoil that waves at other chord positions would have practically the same permissible height. The failure of a 0.016-inch wave to produce transition at the wave may have been due to the fact that the profile did not exactly conform to the shape assumed in the calculations.

It has been found from tests in the 8-foot high-speed tunnel that, under some conditions, a continuous spanwise strip of smooth gummed tape 0.003 inch thick did not cause premature transition but, when the tape was made discontinuous by removing alternate inches of spanwise length, transition occurred at the tape. Three-dimensional waves (fig. 3), however, did not act in this manner; the permissible height was about the same as for two-dimensional waves. Transition occurred on the circular waves 0.020 inch high directly behind the centers of the waves but, behind thinner parts of the waves, transition occurred farther downstream.

Owing to the fact that the principal effect of surface waviness is the effect on the extent of laminar flow, the position of the smooth-wing transition point must be considered in applying the numerical results to other wings.

RIB STITCHING

The drag increments caused by rib stitching on both surfaces are shown in figure 10. The drag was increased about 7 percent for a rib spacing of 6 inches. Figure 11 shows that, as the rib spacing was varied, the drag caused by the stitching varied in direct proportion to the number of ribs. The experimental points indicate a slightly curved line rather than a linear variation but none of the points depart from the straight line shown by more than the experimental error. The stitching over each rib apparently acted independently of that over adjacent ribs even when the spacing was as close as 6 inches.

The rib stitching began 8 percent of the chord from the leading edge so that part of the drag increase was undoubtedly due to the effects of premature transition. The increment attributable to early transition was estimated by assuming that transition occurred at the leading edge of the pinked tape and spread laterally and downstream with a total included angle of 15°. The increment thus estimated is shown by the dashed line in figure 11. Almost one-third of the total drag increase was due to premature transition.

CONCLUSIONS

The most important conclusions derived from the tests described in this note, the numerical examples being taken at a lift coefficient of 0.15 and a Reynolds Number of 10,300,000, are:

1. Surface waviness of a magnitude common to airplane wings will not seriously increase the drag unless the waviness exists on the forward part of the wing, where it may cause premature transition or premature compressibility effects. Waves 3 inches wide by 0.048 inch high, for example, increased the drag about 1 percent when the waves covered the rear 67 percent of both surfaces and 10 percent when they covered the rear 92 percent.

2. A single wave 3 inches wide by 0.020 inch high at the 10.5-percent-chord position on the upper surface was just high enough to cause transition to occur at the wave. The resultant drag increase was 6 percent.

3. Rib stitching corresponding to a rib spacing of 6 inches increased the drag 7 percent; the drag increment

was proportional to the number of ribs for larger rib spacings. About one-third of the increase was due to the premature occurrence of transition at the forward ends of of the stitching.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 27, 1939.

REFERENCES

1. Hood, Manley J.: The Effects of Some Common Surface Irregularities on Wing Drag. T.N. No. 695, N.A.C.A., 1939.

2. Robinson, Russell G.: Sphere Tests in the N.A.C.A. 8-Foot High-Speed Tunnel. Jour. Aero. Sci., vol. 4, no. 5, March 1937, pp. 199-201.

3. von Doenhoff, Albert E.: A Method of Rapidly Estimating the Position of the Laminar Separation Point. T.N. No. 671, N.A.C.A., 1938.

Figure 1.- Airfoil with simulated rib stitching mounted in wind tunnel. The airfoil is set at a large negative angle to show the rib stitching.

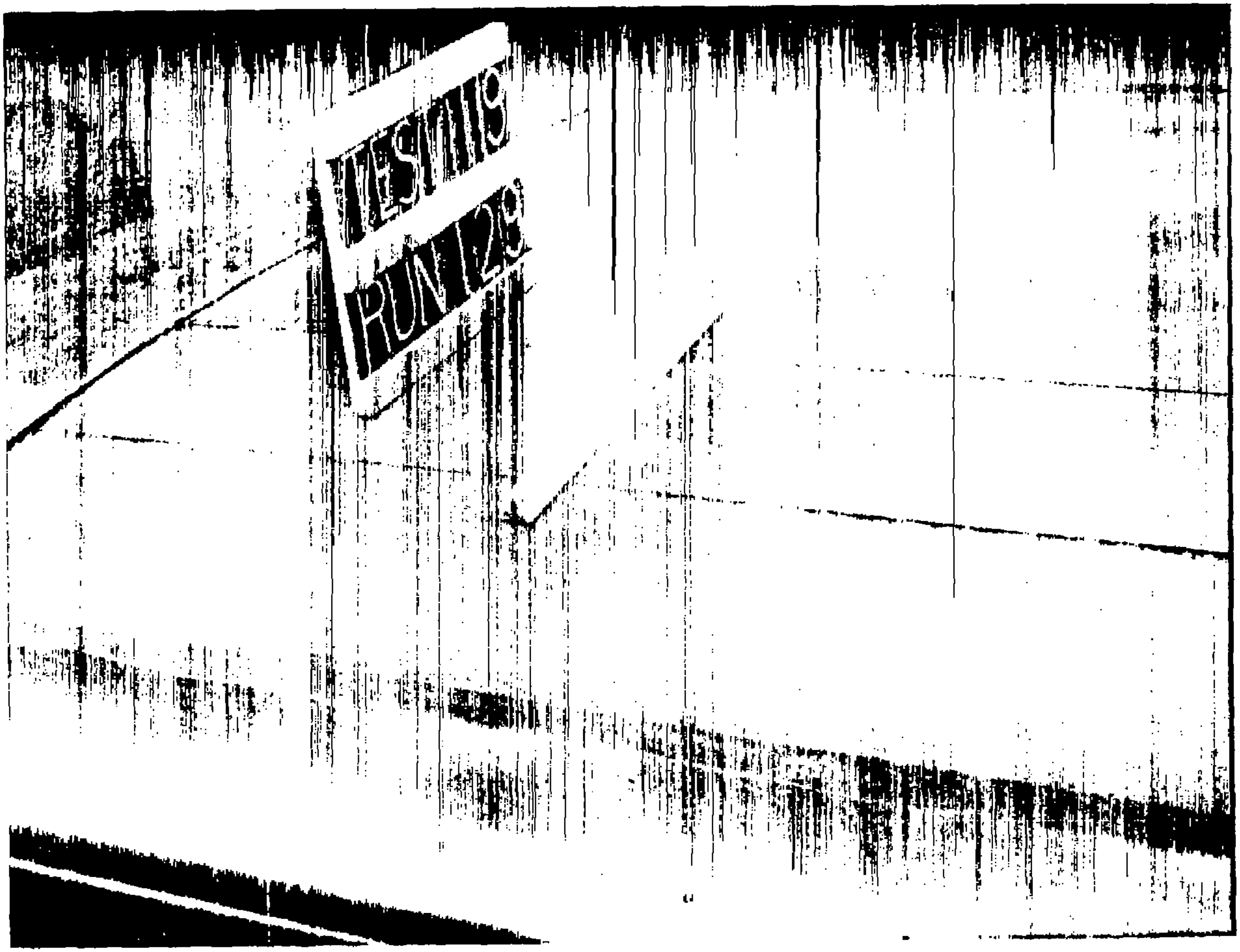

Figure 3.- Waves 7.5 inches wide by 0.120 inch high on airfoil surface.

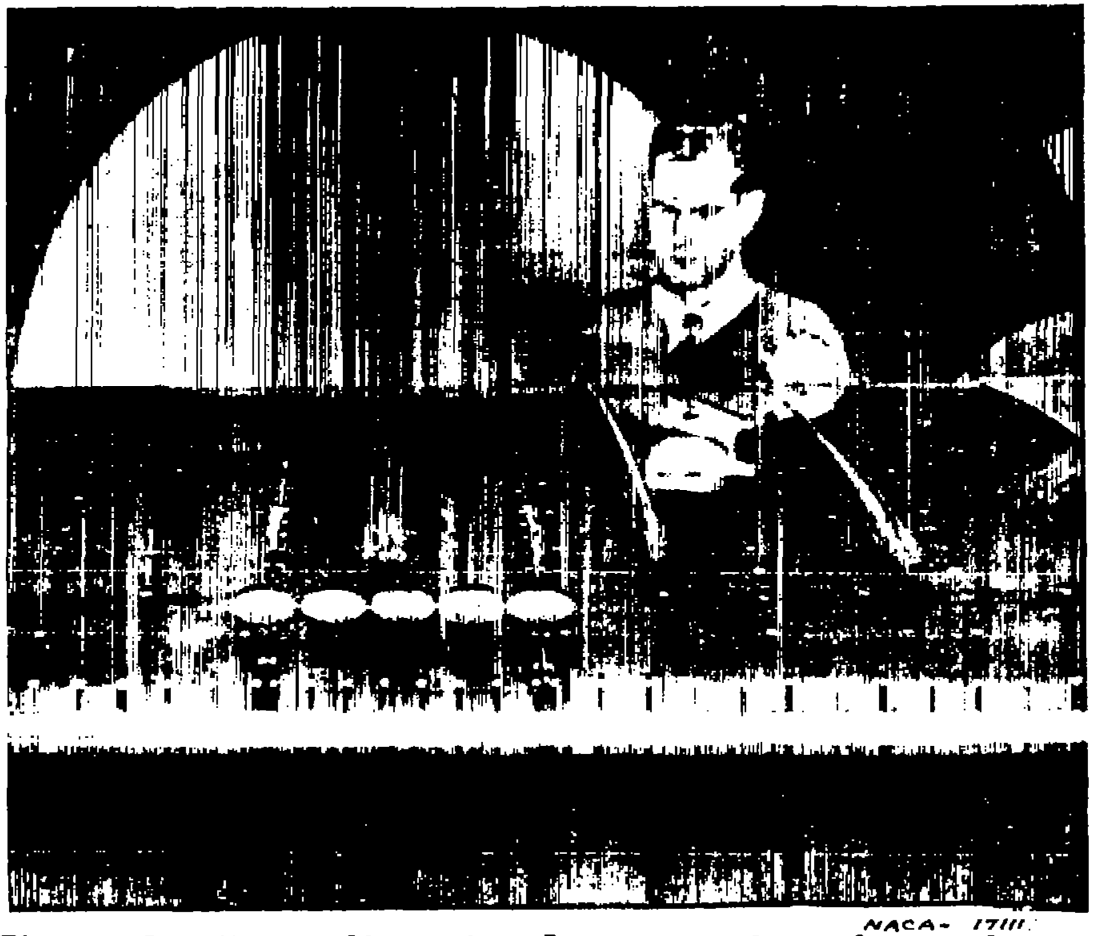

Figure 3.- Three-dimensional waves and surface tubes on airfoil.

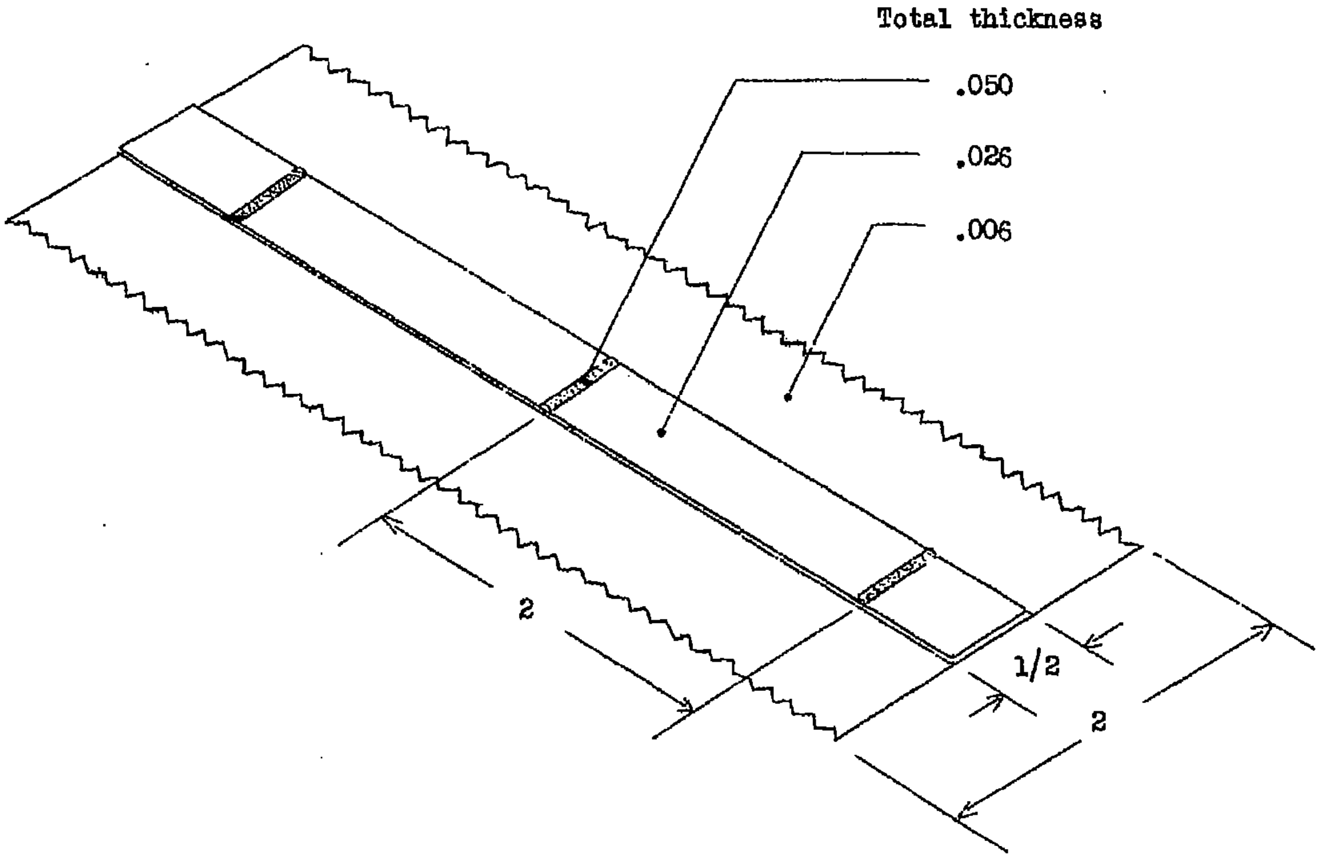

Figure.4.- Simulation of rib stitching. All dimensions are in inches.

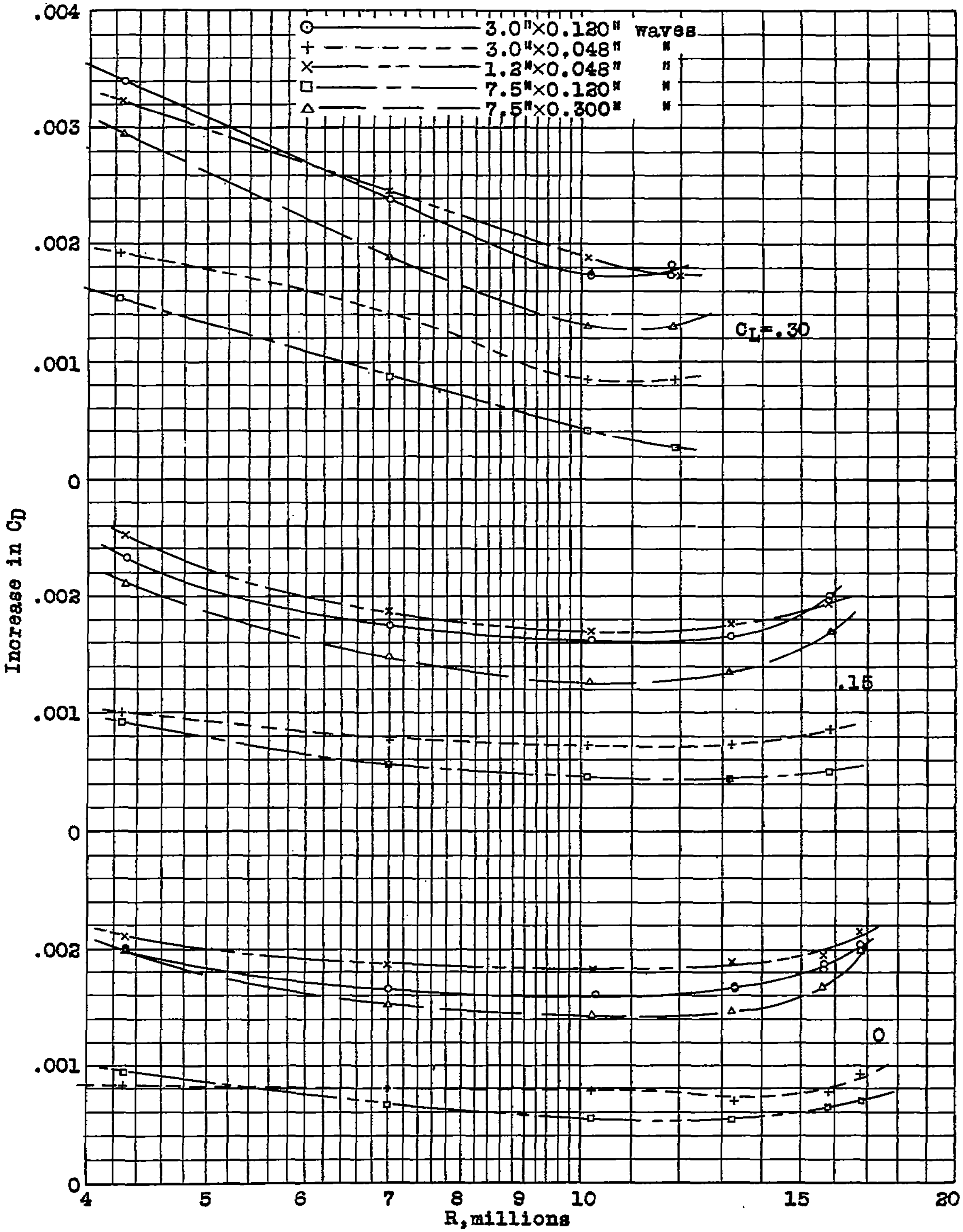

Figure 5.- Drag due to waviness on rear 92 percent of both surfaces of airfoil. Chord, 5 feet.

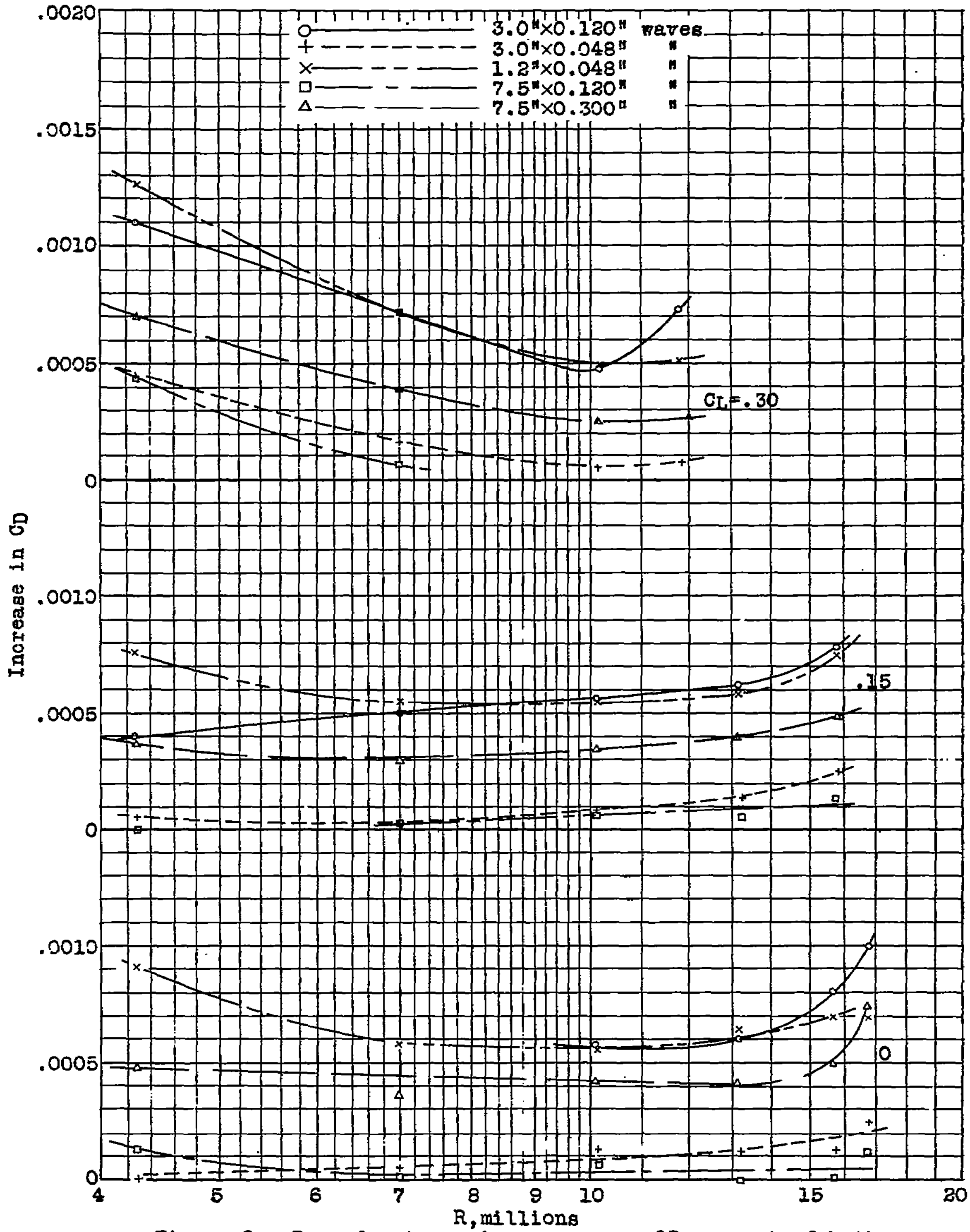

Figure 6.- Drag due to waviness on rear 67 percent of both surfaces of airfoil. Chord, 5 feet.

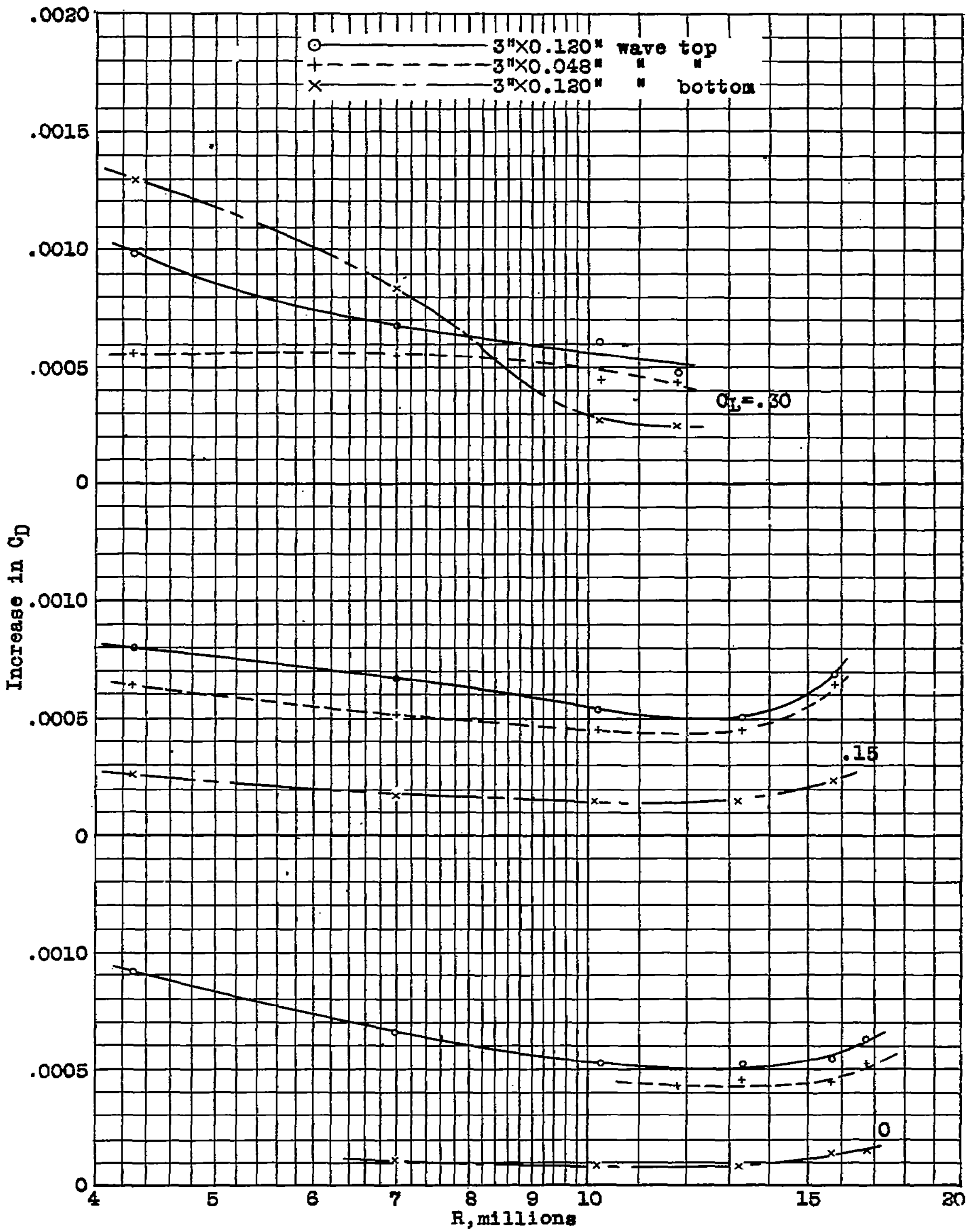

Figure 7.- Drag due to single waves 10.5 percent chord from leading edge. Chord, 5 feet.

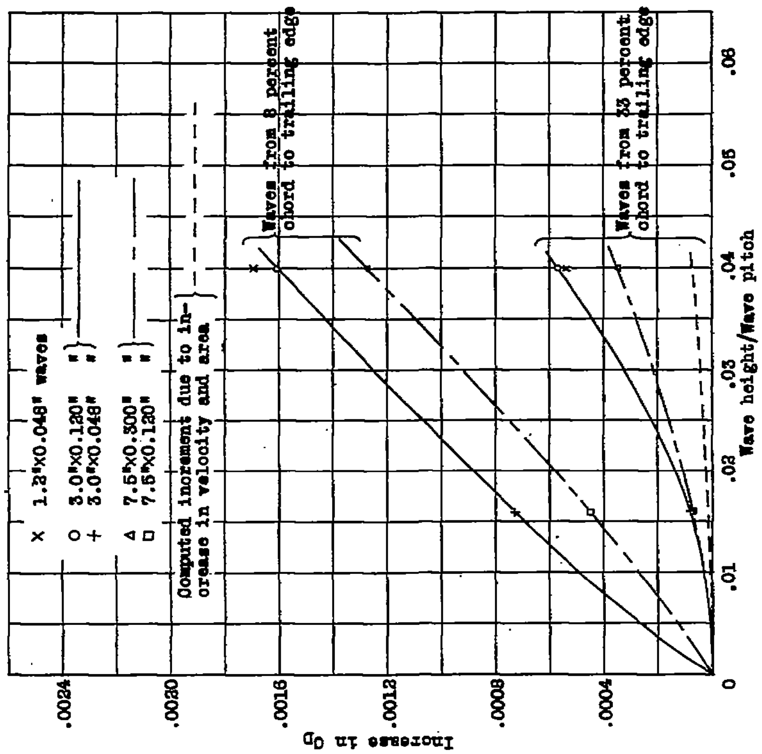

Figure 8.- Variation of drag due to surface waviness with ratio of wave height to wave pitch. Chord, 5 feet; C_L, 0.15; R, 10,300,000.

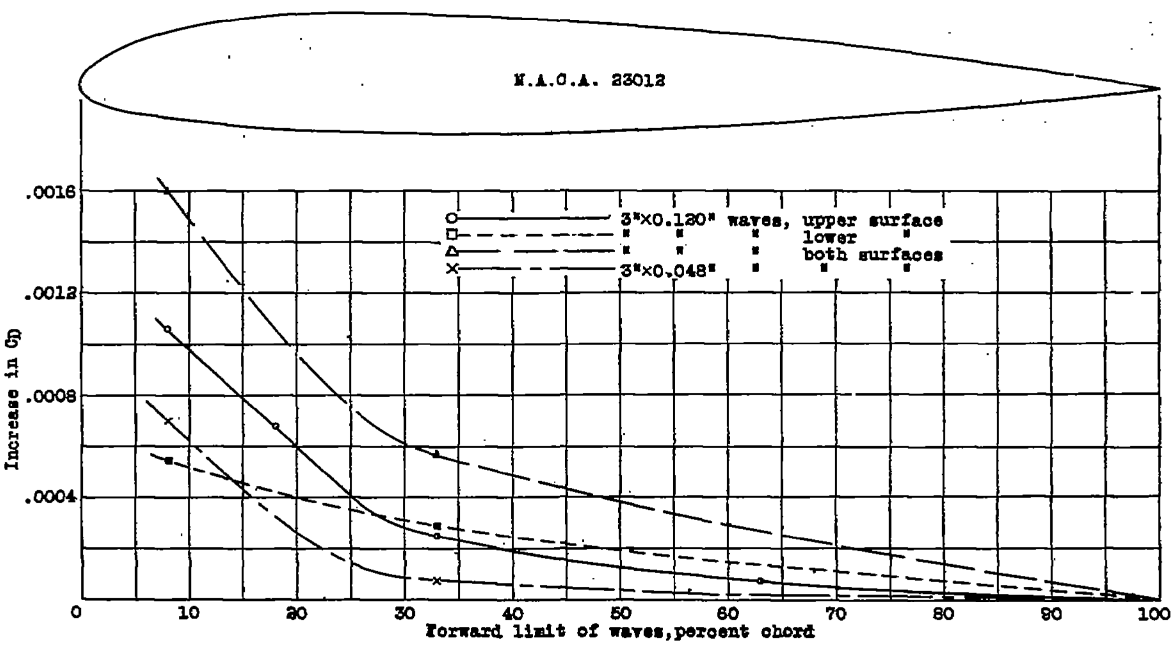

Figure 9.- Variation of drag due to surface waviness with chord position of forward limit of waves. Chord, 5 feet; C_L, 0.15; R, 10,300,000.

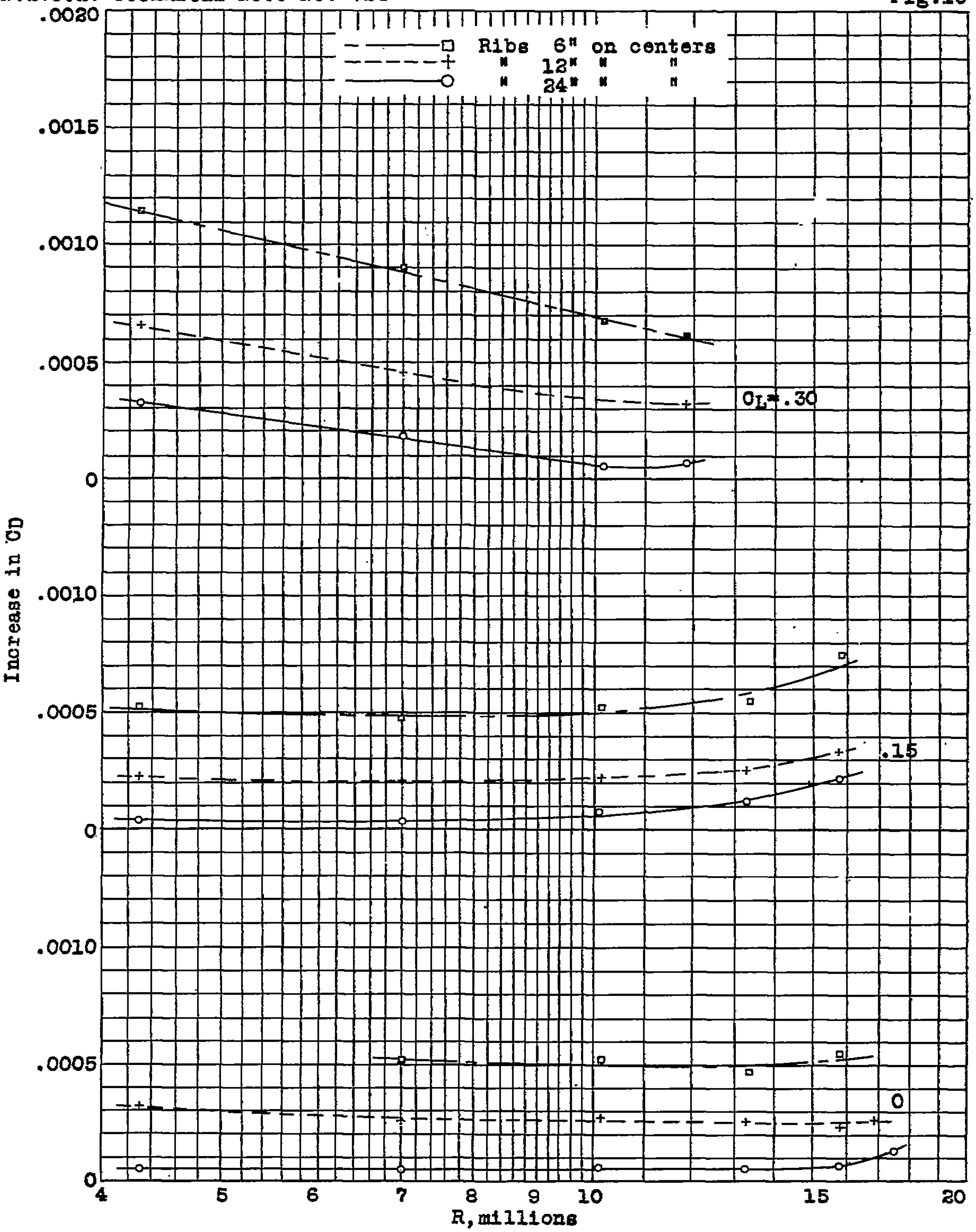

Figure 10.- Drag due to rib stitching. Stitching on both surfaces from 8 percent chord to trailing edge. Chord, 5 feet.

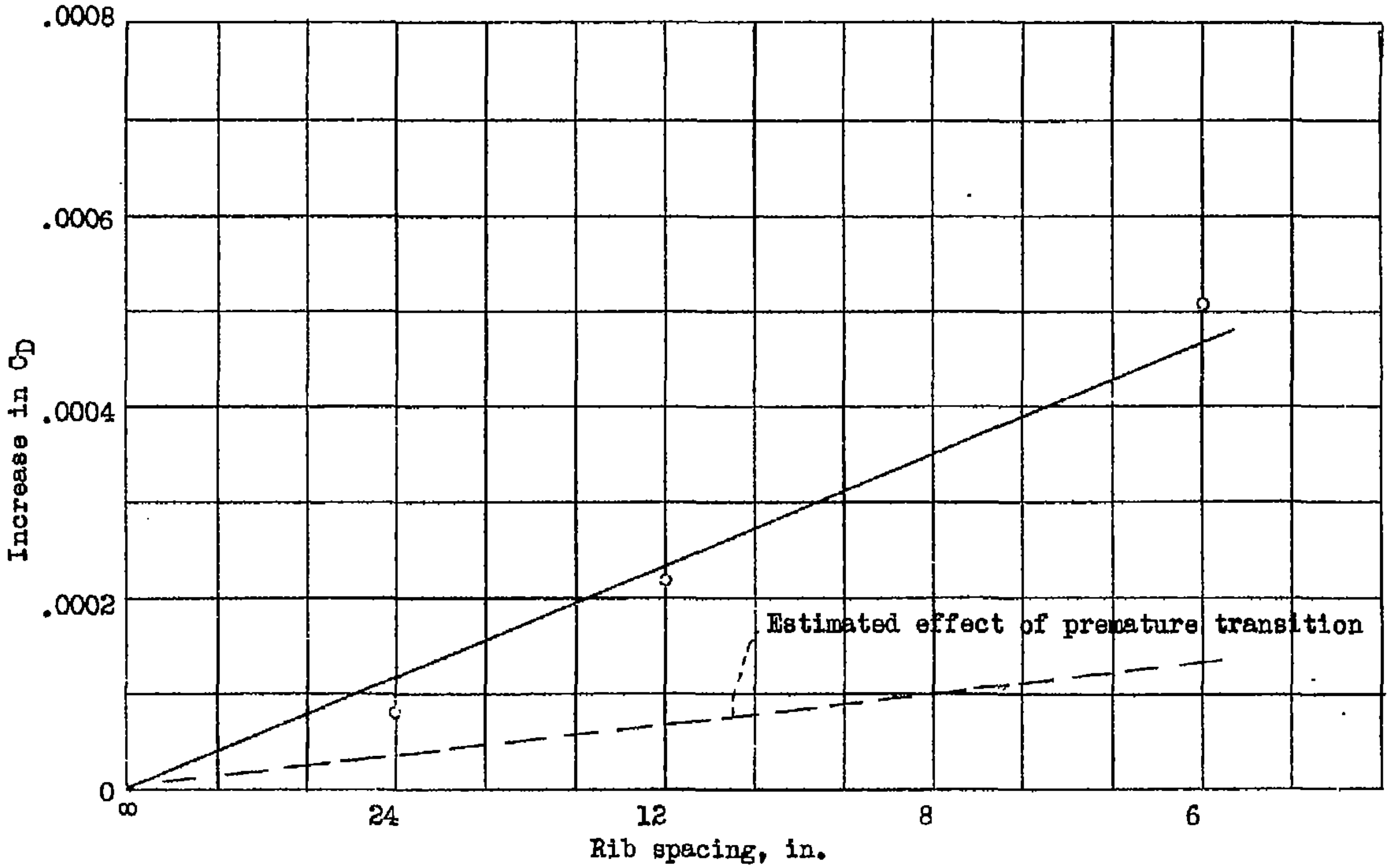

Figure 11.- Variation of drag due to rib stitching with rib spacing. Stitching on both surfaces from 8 percent chord to trailing edge. Chord, 5 feet; C_L, 0.15; R, 10,300,000.

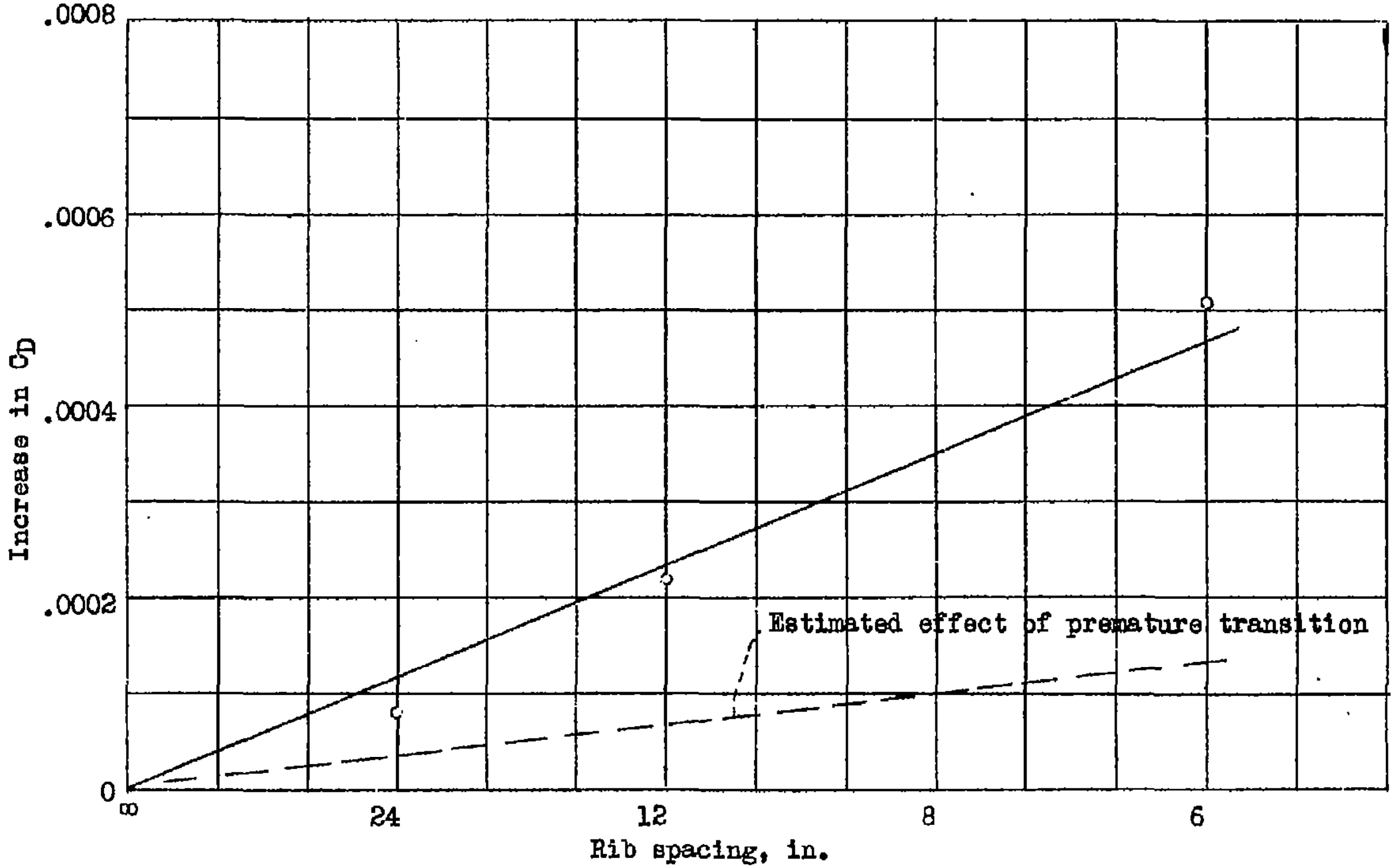

Figure 11.- Variation of drag due to rib stitching with rib spacing. Stitching on both surfaces from 8 percent chord to trailing edge. Chord, 5 feet; C_L, 0.15; R, 10,300,000.